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Effect of In-core Blockage by Debris during Post-LOCA Long Term Core Cooling Phase of Kori-2

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1. Introduction

Generic Safety Issue (GSI) 191 [1] concerns the degradation of heat transfer in the core during Post loss-of-coolant-accident (LOCA) long term core cooling (LTCC) phase by debris which may go through the sump strainer and could be deposited at the core inlet and fuel surface. United State Nuclear Regulatory Commission (US NRC) approved a generic and conservative methodology described in WCAP-16793-NP Rev. 2 [2], and has made use of it for GSI-191 resolution. In Korea, as a part of periodic safety review of Kori-2, an evaluation of thermal hydraulic effect of in-core blockage by debris has carried out based on a conservative emergency core cooling system (ECCS) evaluation method (EM). However, since the ECCS EM has limitations in dealing with recent safety issues, it is necessary to evaluate the safety issues more realistically. This paper describes a realistic approach to evaluate the thermal hydraulic effect of in-core blockage by debris during post-LOCA LTCC of Kori-2. The MARS-KS 1.3 code [3] has been employed for the thermal hydraulic analysis.

2. Hydraulic Evaluation of In-core Blockage

A series of experiments concerning hydraulic effect of in-core blockage by debris in Kori-2 was conducted in 2013 [4] in order to acquire pressure drop by debris deposition at the core inlet and fuel surface. Fig. 1 depicts a nodalization of the experimental facility. The experiments carried out for both hot leg and cold leg break conditions, and relevant inlet flow in each condition was assumed to be constant. Although the debris deposition changes both flow and loss coefficient at the core inlet and the fuel assembly, it is assumed that the debris deposition causes the change in loss coefficient only due to the lack of information on flow area. In addition, it is assumed that the change in loss coefficient by debris deposition happens at the core inlet only in an integral manner. The experiment conducted for 11 and one cases for hot leg and cold leg break conditions, respectively, and all cases were analyzed to evaluate the loss coefficient in each condition. The analysis indicates that the most conservative loss coefficient of hot leg break conditions is 12,926.0 and cold leg break condition has a loss coefficient of 92.77. Those loss coefficients are used for the in-core blockage model for Kori-2

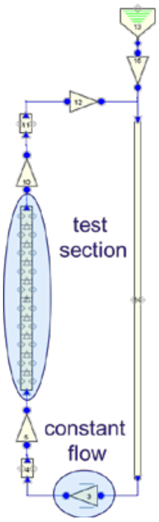


Fig.1. Nodalization for hydraulic test

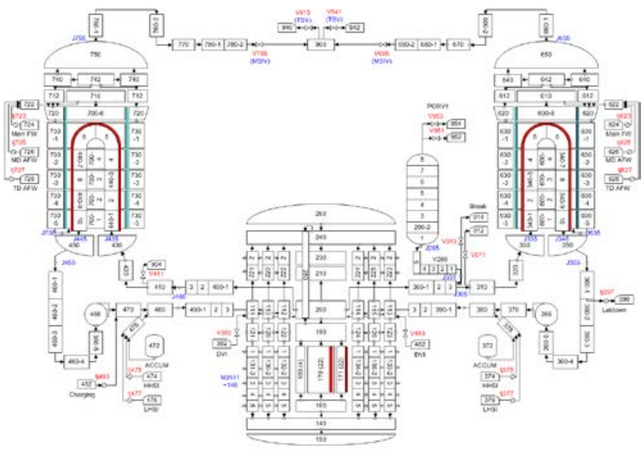


Fig. 2. Nodalization of Kori-2 (hot leg break)

3. Best-Estimate Calculation for LBLOCA

In order to determine the reference case for post-LOCA analysis, best-estimate calculations have been conducted for both hot leg and cold leg break LBLOCA. The analysis carried out based on a thermal hydraulic model, as depicted in Fig. 2, and characteristics of uncertainty parameters developed in previous Kori-2 LBLOCA study [5]. Although the previous study indicates 60% break accident as a limiting case, the double-ended guillotine break has been selected as a reference case in this study since this case is the most limiting from the inventory loss point of view during the post LOCA LTCC. Samples of 124 sets for each break condition were generated by simple ransom sampling and all the calculations were conducted by using MOSAIQUE [6]. Since the purpose of this study is to evaluate the heat transfer degradation by the debris deposition, a reference case in each break condition was selected such that results in the highest peak cladding temperature (PCT) with a probability of 95 % and a confidence level of 95 %.

4. In-core Blockage Model

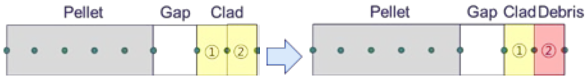
In-core blockage model consists of a hydraulic model at the core inlet to describe the blockage itself and a thermal model for debris deposition at the fuel surface. The hydraulic blockage at the core inlet was done by applying the increased loss coefficients to the flow path to the core when the post-LOCA LTCC started. In this model, it was assumed that the core bypass is totally blocked by debris deposition.

The thermal model should describe the heat transfer through the debris layer formed by debris deposition during the post-LOCA LTCC. This means an additional layer outside the cladding of the fuel rods should be modeled. In principle, the modeling for the additional layer can be done by restarting the heat structure for the fuel rods with additional radial meshes for the debris layer. However, in this case, it is not simple because of the dynamic gap conductance model and deformation model used in the reference calculations. Because of those models, the radial mesh interval in each axial level of the heat structure for the fuel rods is not identical. Thus, it is inevitable to give different radial mesh interval in each elevation when the heat structure is restarted. However, this is impossible in MARS-KS because a heat structure allows a single radial mesh interval for whole axial levels. In order to describe the heat transfer phenomena avoiding such a limitation, two different thermal models has been developed.

4.1 Cladding replaced by Debris (case 1)

There is a negligible temperature gradient through the cladding and the cladding temperature after core quenching is low enough to avoid additional deformation. In addition, the cladding thickness is 22.5 mils which is close to a thickness of the debris layer of 16.7 mils calculated by a conservative LOCADM [7]. Based on the above observation, in this model, the cladding is replaced by debris when the post-LOCA LTCC starts. This model can be done by replacing the material properties of the cladding with the properties of debris, as depicted in Fig. 3(a). Thus, the restart of the heat structure is not needed, so that the deformed geometry can be used during the calculation without any problem. Because there is no cladding in this model, it is presumed the largest temperature increase due to the heat transfer degradation by debris deposition. Thus, the most conservative result is expected by this model.

(a)



(b)

Fig. 3. Modeling options for debris layer

4.2 Hybrid Model (case 2)

The dynamic gap conductance model plays a very important role in determining the PCT during LOCAs because the model decides the thermal resistance through the gap. However, it is obvious that the variation in gap conductance during the post-LOCA LTCC is negligible due to the low and constant temperature. Thus, the dynamic gap conductance model does not play an important role in determining the cladding temperature during the post-LOCA LTCC phase. Therefore, for realistic evaluation, it is essential to use the dynamic gap conductance model during LOCAs and the effect of the model can be ignored during the post-LOCA LTCC phase.

A hybrid model has been developed to cope with both conditions. At first, the cladding is modeled by using two difference regions, regions 1 and 2, as depicted in Fig. 3(b). Region 2 has a thickness of 16.7 mils from LOCADM.

For the LOCA calculation, the region 1 and 2 should be composed of a single material, Zircaloy, because the dynamic gap conductance model in MARS-KS allows only three materials (pellet, gap, and cladding) for the fuel. Thus, Regions 1 and 2 are described by using materials A, for example. By using this model, the LOCA calculation is conducted with normal fuel configuration.

The calculation for the post-LOCA LTCC phase is conducted by restarting the calculation from the end of normal LOCA calculation. In order to model the debris layer in this calculation, a modification to the code was performed. By this modification, if the material for the last radial node of a heat structure is material A, the code internally changes the material to material B which has the properties of the debris layer. Thus, the calculation for the post-LOCA LTCC phase can be conducted with the debris layer.

Actually, this model also cannot describe the physical phenomena as is because of reduced cladding thickness. However, the temperature gradient through the cladding is very small due to high conductivity and the thermal inertia of the cladding does not play an important role during the post-LOCA LTCC phase due to the stable temperature behavior. Therefore, the hybrid model is expected to be closest to the actual.

5. Results and Discussion

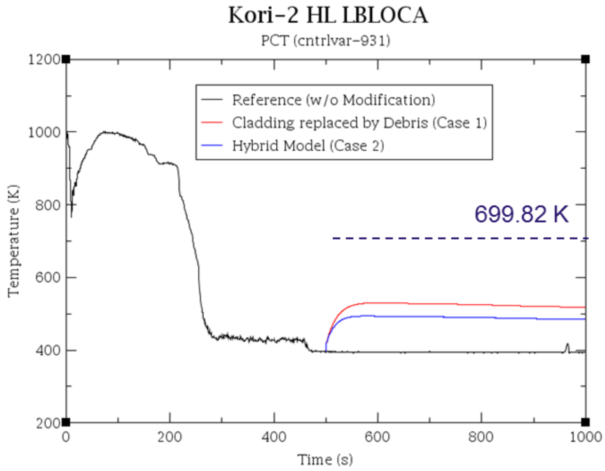
The effect of heat transfer degradation by debris deposition during the post-LOCA LTCC phase has been evaluated by thermal hydraulic analyses using MARS-KS. The calculation for normal LOCA was conducted for 500 sec. The post-LOCA LTCC is assumed to start at 500 sec and the debris deposition happens at 500 sec as well. The thermal conductivity of debris is assumed to be constant as 0.17296 W/m-K (= 0.1 BTU/ft-hr-^{o}F) based on reference [2].

5.1 Hot Leg Break LBLOCA

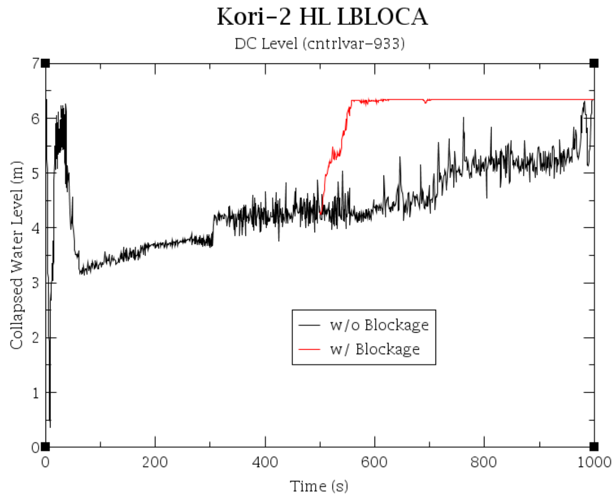
Fig. 4 depicts the PCT and downcomer level during the hot leg LBLOCA. As presumed, case 1 results in higher PCT than case 2 due to the conservative modeling for the debris layer. It is found that the PCT in each case is increased by 136 K and 100 K because of heat transfer degradation by debris deposition at the fuel surface and reduced flow by in-core blockage. However, the PCTs in both cases are lower than the safety limit of 699.82 K (=800 ^{o}F) suggested by WCAP methodology [2]. In Fig. 4(b), it is indicated that the downcomer level above the core inlet elevation is increased as in-core blockage happens. This is because the flow though the core inlet is decreased due to the in-core blockage. The result reveals that there is enough available driving head during the post-LOCA LTCC phase.

5.2 Cold Leg Break LBLOCA

Fig. 5 depicts the PCT and downcomer level during the cold leg LBLOCA. As same as the hot leg break, case 1 results in higher PCT than case 2 due to the conservative modeling for the debris layer. It is found that the PCT in each case is increased by 125 K and 88 K because of heat transfer degradation by debris deposition at the fuel surface and reduced flow by in-core blockage. However, in this case, the PCT increase is dominated by the heat transfer degradation by debris deposition since the impact of hydraulic in-core blockage is much smaller than the hot leg break. As same as the hot leg break, the PCTs in both cases are lower than the safety limit of 699.82 K (=800 ^{o}F). In Fig. 5(b), it is indicated that the downcomer level above the core inlet elevation is almost identical to the case without in-core blockage. This is because the flow though the core inlet does not change much due to small impact of in-core blockage. The result also reveals that there is enough available driving head during the post-LOCA LTCC phase.



(a) Peak cladding temperature

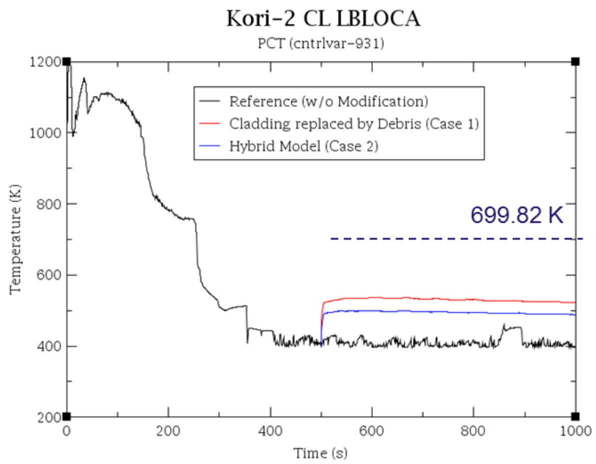


(b) Downcomer level above core inlet elevation (case 2)

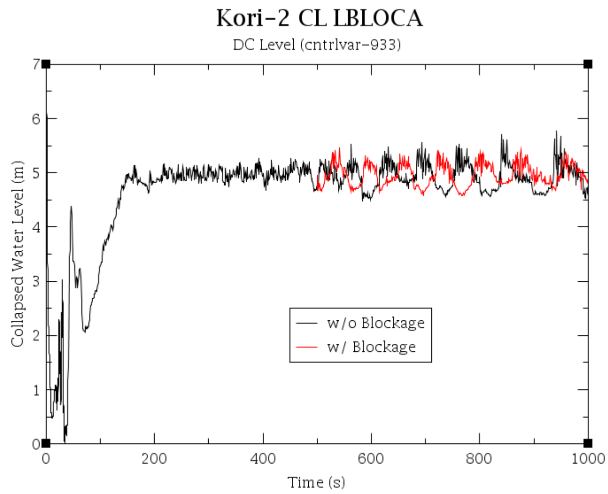
Fig. 4. Results for hot leg LBLOCA

6. Conclusion

The effect of in-core blockage by debris has been evaluated by thermal hydraulic analyses with MARS-KS. In order to evaluate the heat transfer degradation by debris deposition a conservative and realistic fuel models has been developed, respectively. The analysis indicates that the PCT during the post-LOCA LTCC phase increases due to the heat transfer degradation by debris deposition and flow reduction by in-core blockage. It is also found that the PCT increases more in hot leg break case because of a larger reduction in core flow by higher pressure drop at the core inlet. However, it is revealed that the PCT in all cases are far below the acceptance limit of 699.82 K (800 ^{o}F) suggested by WCAP methodology.



(a) Peak cladding temperature



(b) Downcomer level above core inlet elevation (case 2)

Fig. 5. Results for cold leg LBLOCA

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